

The effects of snowpack grain size on satellite passive microwave observations from the Upper Colorado River Basin

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Abstract. Understanding the passive microwave emissions of a snowpack, as observed by satellite sensors, requires knowledge of the snowpack properties: water equivalent, grain size, density, and stratigraphy. For the snowpack in the Upper Colorado River Basin, measurements of snow depth and water equivalent are routinely available from the U.S. Department of Agriculture, but extremely limited information is available for the other properties. To provide this information, a field program from 1984 to 1995 obtained profiles of snowpack grain size, density, and temperature near the time of maximum snow accumulation, at sites distributed across the basin. A synoptic basin-wide sampling program in 1985 showed that the snowpack exhibits consistent properties across large regions. Typically, the snowpack in the Wyoming region contains large amounts of depth hoar, with grain sizes up to 5 mm, while the snowpack in Colorado and Utah is dominated by rounded snow grains less than 2 mm in diameter. In the Wyoming region, large depth hoar crystals in shallow snowpacks yield the lowest emissivities or coldest brightness temperatures observed across the entire basin. Yearly differences in the average grain sizes result primarily from variations in the relative amount of depth hoar within the snowpack. The average grain size for the Colorado and Utah regions shows much less variation than do the grain sizes from the Wyoming region. Furthermore, the greatest amounts of depth hoar occur in the Wyoming region during 1987 and 1992, years with strong El Niño Southern Oscillation, but the Colorado and Utah regions do not show this behavior.

Introduction

The seasonal snowpack in the mountains of the Upper Colorado River Basin is a major source of water for a large part of the western United States. Effective management of this vital resource requires accurate and timely estimation of the snowpack water equivalent over the entire region. Satellite passive microwave observations have the potential to determine synoptically snowpack water equivalent over large areas, independent of solar illumination. This capability, when coupled with the global satellite passive microwave data set that is now 15 years in length, will also be a powerful tool in global and regional climate change–snowpack studies. For both of these cases, accurate algorithms are necessary to extract the water equivalent from the satellite observations.

The brightness temperature of the snowpack is inversely related to the water equivalent of the snowpack. As the water equivalent increases, the snowpack scatters more of the upwelling radiation from the ground. However, this effect is limited by the increasing emission of the thickening snowpack

[Chang *et al.*, 1976]. The scattering is not only dependent on the water equivalent of the snowpack, but also on the size of the snow grains, which produce the scattering. The scattering efficiency of the individual grains increases with increasing grain size, and as the wavelength and grain sizes become comparable, the scattering greatly increases. Snowpack microwave emissions also depend on the internal structure of the snowpack: vertical distributions of grain size, density, and the snowpack stratigraphy.

Matzler [1987] gives a thorough review of the interactions that occur between microwaves and a snowpack, describing both theoretical and experimental investigations. The theoretical studies include the following. Chang *et al.* [1976] applied Mie scattering theory to explain the effect of scattering by snow grains in a snowpack. Stiles and Ulaby [1980 a, b] determined the behavior of the microwave emission by a snowpack as a function of its water equivalent and grain size structure. Chang *et al.* [1980] determined the dependence of the 37-GHz brightness temperature on both the snow water equivalent and the grain size for spherical grains up to 0.5 mm in radius. Chang *et al.* [1980] and Armstrong *et al.* [1993] show the strong sensitivity to grain size. For example, an increase in radius from 0.3 to 0.5 mm for a snowpack with a water equivalent of 0.5 m will reduce the 37-GHz brightness temperature by more than 50 K. These calculations were car-

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at an elevation of 2512 m, and digital elevation data within the SMMR pixel containing this site show that the elevation within this pixel varies from 2250 to 2810 m, with an average pixel elevation of 2411 m. Given any reasonable estimate of the atmospheric lapse rate ($\sim 3^{\circ}\text{C km}^{-1}$), the air temperature at all elevations within the pixel was well below the freezing point for the entire period, and hence the snowpack throughout the entire pixel must have been dry during these observations.

Microwave radiation emanating from a snowpack depends on the grain size distribution as well as the density and number of the scattering grains. Figure 2 shows an NGR map of the Colorado drainage basin for March 2, 1987. The blank areas are snow-free, as determined by the criteria of *Josberger and Beauvillain* [1989]. The Wyoming region when compared with the Colorado/Utah regions shows equally high or higher values of NGR, despite the fact that the Colorado/Utah snowpacks were generally deeper. The reason for this behavior becomes clear upon examination of the average grain size depicted in Figure 4 for the 1987 snow year; the average grain size in the Wyoming snowpack was about twice that in the Colorado/Utah snowpacks.

In order to explore this phenomenon further, we have used a scattering model developed by *Chang et al.* [1987] to calculate brightness temperatures and NGR values for a single-layer snowpack with uniform density and grain size. Figure 8 shows the results of these calculations for spherical grains with radii of 0.3 and 0.5 mm and a density of 300 kg m^{-3} . The NGR values increase not only with increasing water equivalent, but also with increasing grain size. Furthermore, the dependence on grain size is nonlinear and becomes stronger as the grain size begins to approach 8.1 mm, the wavelength of the 37-GHz observations. This nonlinearity accentuates the differences in microwave characteristics that result from small differences in grain size.

The field observations show that the snowpack in the mountains of the Upper Colorado River Basin consists of two

layers: an upper layer of well-rounded grains with a radius of approximately 0.4 mm and a lower depth hoar layer of much larger and more irregular grains. The thicknesses (or water equivalents) of the various layers in a snowpack enter into the determination of whether or not radiation emanates entirely from the top layer, from several layers, or from all the layers and the substrate. An estimate of these effects can be obtained by examining the snowpack thickness that gives an optical thickness of 1, the e -folding length scale. For the upper layer, with a grain radius of 0.4 mm, the thickness is approximately 1.6 m at 18 GHz, while for 37 GHz the thickness is approximately 0.3 m. For the lower layer the selection of parameters to be used in the model is made more difficult by the random sizes and shapes that are typical of the depth hoar layer. The snow grains in the lower layer typically have a major dimension of 5 mm and a minor dimension of ~ 2 mm, a thickness of ~ 1 mm, and may be loosely bonded together in clusters 10 to 15 mm long. To approximate the scattering in the lower layer, we took an effective scattering radius of 1.5 mm, which yields snowpack thicknesses of about 0.1 m at 18 GHz and 10 mm at 37 GHz. Thus it takes relatively little depth hoar to trap any radiation emanating from the substrate and to yield low brightness temperatures or high NGR values.

Sturm et al. [1993] measured the emissivity at 18 and 37 GHz of tundra and taiga snowpacks in Alaska using sled-mounted radiometers. Both of these snowpack types contain large amounts of extremely well-developed depth hoar as a result of the extreme temperatures and thin snowpack, <1 m. The results show that the emissivities or brightness temperatures of both snowpacks reach a minimum value when the depth hoar layer is approximately 0.3 m thick and that there is little correlation with the water equivalent beyond this thickness. However, in the Upper Colorado River Basin, *Josberger et al.* [1989] show that there exists a strong correlation between the snowpack water equivalent point measurements from the SNOTEL system, which can attain values of 1 m, and SMMR observations. The depth hoar layer in the mountains of the Upper Colorado has smaller grains and is usually less well developed than in Alaska, and it makes up a smaller fraction of the snowpack.

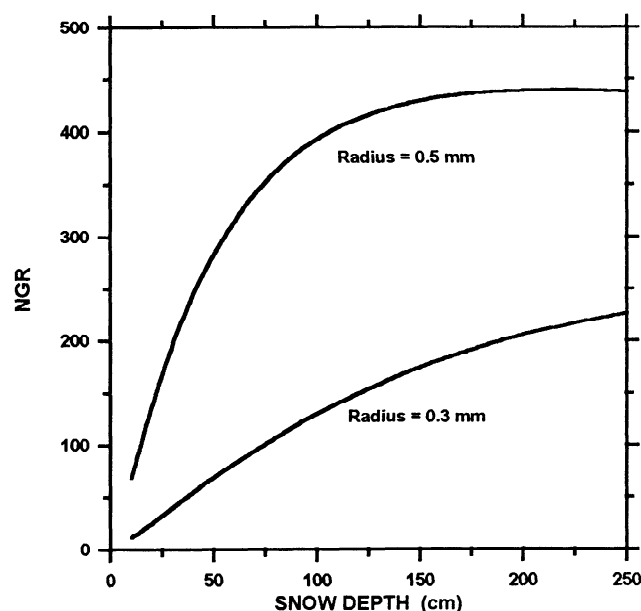


Figure 8. The behavior of NGR as a function of water equivalent and grain size from a single-layer scattering model with a snow density of 300 kg m^{-3} .

Conclusions

The passive microwave emissions from the snowpack in the Upper Colorado River Basin depend on both the snowpack water equivalent and the snowpack grain size. Field observations of the grain size from 1984 to 1995 show that the snowpacks in the Wyoming region have a greater average grain size than do the snowpacks in the remainder of the basin. This grain size distribution, coupled with the strong dependence of microwave scattering on grain size, yields the strong passive microwave signals that are only observed in the region surrounding the headwaters of the Upper Green River in Wyoming.

The snowpacks in the entire basin typically consist of an upper layer with rounded grains 0.5–1.5 mm in diameter that are the result of equitemperature metamorphism. The lower layer consists primarily of depth that is formed by temperature gradient metamorphism. The depth hoar grains are stepped, cuplike crystals with a major dimension of up to 5 mm, and these grains may be loosely bonded together in long clusters. The depth hoar layer forms early in the winter, November and

December, and then ceases to grow when the vertical temperature gradients relax.

Annual and regional variations of the snowpack grain size result from changes in the relative proportion of depth hoar within the snowpack. The snowpack in the Wyoming region displays the most variability, with average grain sizes from 1.2 to 2.8 mm, with the largest average grain sizes occurring during El Niño periods. The snowpacks in the Colorado and Utah regions generally have smaller grains, are composed mostly of rounded grains, and have a smaller interannual variation when compared with the Wyoming snowpack. Also, there is no correlation between ENSO and grain size variability for the Colorado and Utah snowpacks.

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